Solution 8. Concept

Solution 8: AI-based smart control system of PV plants with batteries with weather and electricity market forecasts to maximise the energy trading.

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List of Acronyms

AGR	Avoid Grid Reconstruction
AI	Artificial Intelligence
ARIMA	Auto Regressive Integrated Moving Average
BESS	Battery Energy Storage System
CM	Capacity Market
DT	Digital Twins
EMS	Energy Management System
FR	Frequency Regulation
GARCH	Generalized Autoregressive Conditional Heteroskedasticity
GRU	Gated Recurrent Unit
IoT	Internet of Things
LSTM	Long Short-Term Memory
ML	Machine Learning
MSC	Maximization of Self-Consumption
PS	Peak Shaving
RNN	Recurrent Neuronal Network
SARIMA	Seasonal ARIMA
TOU	Time of Use

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Keywords list

- Simulation
- Control
- Forecasting
- Sun tracking
- Batteries

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1. Executive summary

This document presents the concepts at the root of WP3 solutions, all of them about the Control of PV plants to optimise their performance. This WP3 is divided into two differentiated tasks:

- Task 3.1: Development and demonstration of a simulation tool and control system to maximize the performance of PV plants with sun tracking systems.

- Task 3.2: Development and demonstration of a control system to maximize the performance and energy trading of PV plants with batteries. In turn, this task is divided into two:

  - Chapter A: Battery control system
  - Chapter B: Electricity Market Forecast

Regarding T3.2, PVOP will develop a PV plant control system that will integrate a Smart Energy Management System (EMS) based on predictions of weather conditions (including extreme events) and an AI-based electricity market predictor. The concept at the root of this solution is the following: the EMS will receive inputs from sensors, electricity price databases, meteorological databases and Electricity Market Analysts predictor that will allow the EMS to select, in a hourly basis, the best strategy to maximize the profitability of the PV asset. Regarding, the forecast prices in the electricity market, a new concept will be implemented that is thought to be decisive: the stochastic analysis of the forecasts.

For the validation of these solutions, experiments and specific KPIs for both, the implementation of control strategies for batteries and for the electricity market forecast tool, have been proposed.

2. Introduction

This document presents the first deliverable of WP3 (Control of PV plants to optimize their performance), and it explains the main objectives to be reached, the techniques used for that and the KPIs defined for the validation of the different solutions.

This WP3 is divided into two differentiated tasks, and one of them is as well separated into two main lines of work. The deliverable is structured accordingly:

- Task 3.1: Development and demonstration of a simulation tool and control system to maximize the performance of PV plants with sun tracking systems.

- Task 3.2: Development and demonstration of a control system to maximize the performance and energy trading of PV plants with batteries.

    - Chapter A: Battery control system
    - Chapter B: Electricity Market Forecast

This document is focused on Task 3.2 and describes the Solution 8: AI-based smart control system of PV plants with batteries with weather and electricity market forecasts to maximise the energy trading.

3. Task 3.2: Control system to maximise the performance and energy trading of PV plants with batteries

The second task of WP3 focuses on the development and validation of an advanced control system that permits to optimise the performance of PV plants with batteries. There are two differentiated lines of work involved in this task that will be explained in two separate chapters:

- The development of the solutions for a smart Energy Management System (EMS) that will include different strategies for battery management (Chapter A)

- The development of an AI-based electricity market predictor that will be an input for the smart EMS in some of the control strategies (Chapter B)

3.1. Chapter A: Smart Energy Management System

3.1.1. Introduction

Background

Photovoltaics has been remarkably successful in integrating into the electricity mix and reducing electricity prices during solar hours. To continue this progress, various stakeholders are keen on advancing **Battery Energy Storage Systems (BESS)**:

- **Consumers** are benefiting from the electricity low-price scenario during sunny hours, but to save money at night, they must implement load management strategies (adjusting consumption patterns to shift electricity use from high-price periods to low-price periods) or adopt Behind the Meter (BtM) storage solutions.

- **Photovoltaic Developers** are also interested in promoting Front the Meter (FtM) storage. In a saturated photovoltaic (PV) market, the low price of electricity is reducing profits and hindering new investments in PV plants. Standalone and hybrid Battery Energy Storage Systems (BESS) projects will facilitate the integration of additional PV power into the grid by balancing supply and demand, improving grid stability, and enhancing the economic efficiency of electricity markets.

- **Grid operators** would significantly benefit from energy storage solutions. As PV power generation drops off rapidly in the evening while electricity demand remains high, this creates a sharp increase in net demand, known as the "ramp-up" period, requiring fast and flexible power sources. Storing excess PV power generated during the day and releasing it in the evening will mitigate the "Duck Curve," reducing the challenge for grid operators to bring other power sources online quickly.

BESS is a mature technology with a promising trend of decreasing costs. The state of the art of battery integration is dominated by batteries in PV self-consumption installations. Although the integration of batteries in utility-scale PV plants is starting to be a trend in several European countries, its use is limited due to a lack of regulation and incentives beyond electricity arbitrage. This is expected to change with the approval of capacity markets and other incentives by European governments. Once these measures are established, a massive introduction of BESS into the market is anticipated.

PVOP objectives

This report constitutes the first deliverable of the WP 3 of PVOP project. This work package is entitled “Control of PV plants to optimize their performance”. WP 3 is divided in two main tasks, T3.1 and T3.2. This part is devoted to T3.2 which is entitled **“Development and demonstration of control systems to maximize the performance and energy trading of PV plants with batteries”** and aims to develop the results R3 and R5 of the project.

The **main objectives** of T3.2 are:

1) To develop and demonstrate technical solutions for the control of PV plants to **maximize their performance**.

2) To **optimize the energy trading** of PV plants with batteries.

The PV scenario integrating batteries is very diverse. Here we propose to develop the solutions for a smart EMS that will include different strategies for battery management. This will be accompanied by **AI-based electricity marked predictor** (developed ad-hoc by the PVOP team, according to the plan detailed in **chapter B**) and **weather event forecast** (which will be bought from one of the available databases in the market). These two inputs are the key to develop an advanced control system and to truly optimize the battery integration.

The following sections of this chapter detail the **PVOP proposal** (how will the smart EMS operate, and what battery control strategies will be implemented) and the **Key Performance Indicators (KPIs)** that are believed to better quantify the benefits of this innovative solution.

3.1.2. PVOP proposal: concept

PVOP will develop a PV plant **control system** that will **integrate a Smart Energy Management System (EMS)** based on **predictions of weather conditions** (including extreme events) and an **AI-based electricity market predictor**. The EMS will be able to **manage the battery according to the most suitable control strategy** (among several strategies that will be described further in this document), receiving as input the data from weather and electricity market forecasters. By considering the weather forecasts (and the associated estimated PV productions) and the expected market prices, the Smart EMS will evaluate and implement the most appropriate management strategy for each hour.

Additionally, the EMS and the business model will also be developed **for centralized storage (**not attached to a specific PV plant). This storage would be installed at some point in the low or medium voltage rings, allowing the battery to be charged directly from the grid or from any PV plant in the ring through bilateral contracts. This would have **several advantages**: cost reduction due to economies of scale, greater access to PV generation, a greater number of charge and discharge cycles with the corresponding increase in profitability, and access to secondary regulation markets that have a higher average price.

Regarding the battery control strategies that will be developed and implemented, they have been selected because of their usefulness for some of the most interesting **applications for batteries** nowadays:

1) **PV plants for electricity generation.** They represent the biggest share in the PV market and are the most mature in technology and regulation. Batteries can help to improve the energetic and economic performance of PV plants (i.e. storing electricity when the selling price is low, when the evacuation point is overloaded…), but advanced control algorithms are necessary to guarantee the economic feasibility.

2) **Large self-consumption installations** (>1MW$_p$). Installed typically in industrial facilities or in very large neighbourhoods. Batteries are essential to optimize the energy flows between different consumers, optimizing the self-consumption and the self-sufficiency of the system.

3) **New niches:** less explored and with bigger room for innovation. The project partners believe that there are two applications in particular that will become relevant in the near future:

   - **Mining:** it is worth noting that the mining industry consumes a staggering amount of energy, around 11% of the world's total energy consumption. A considerable part of this energy currently comes from fossil fuels and mines are responsible for 4-7% of global greenhouse gas emissions. In this sense, renewable energies not only help to avoid the rising costs of fossil fuels, but also significantly reduce greenhouse gas (GHG) emissions. By adding PV generators without batteries, 20% of the diesel consumption during the day can be saved, but to go beyond this limit it is necessary to have them. In addition, PV generators allow to turn most of the diesel generators off. However, precautions must be taken regarding PV power fluctuations: diesel generators take some minutes to be turned on, so batteries are fundamental to guarantee the stability of the system during these critical periods.

   - **Energetic communities:** similar to shared self-consumptions in many aspects of, but different from a regulatory point of view. Mainly, the energetic community can be registered as an actor of the electricity market, being allowed to distribute, share, accumulate or sell the electricity produced.

There are different operating modes contributing to generating revenue for a Battery Energy Storage System (BESS) and enable a quicker return on investment. In fact, considering the actual cost of BESS a "revenue stacking" strategy is needed to assure an acceptable return on investment. Revenue stacking refers to the strategic utilization of multiple revenue streams and cost-saving opportunities to maximize the financial returns of a BESS. Table 2 shows how different operating strategies contribute to revenue stacking and facilitate a swift amortization of the investment:

Operating modes	Revenue Generation	Return on Investment
Time of Use (TOU) Arbitrage	TOU arbitrage involves charging the battery during off-peak hours when electricity prices are low and discharging during peak hours when prices are high.	Consistently leveraging daily market fluctuations generates regular income, contributing to the overall revenue stack and

	This process allows the BESS to capitalize on price differentials by buying low and selling high	shortening the payback period.
Peak Shaving (PS)	Peak shaving reduces the demand charges on electricity bills by lowering the peak demand during high-consumption periods. By discharging the battery during peak times, businesses can avoid the highest tariff rates associated with their peak usage.	A significant reduction in demand charges, which can constitute a large portion of industrial and commercial electricity bills, directly improves net income. This cost-saving measure adds to the revenue stack, accelerating the return on investment. This operation mode can avoid Grid reconstruction (AGR).
Maximization of Self-Consumption (MSC)	This mode ensures that energy generated by a PV system is used as much as possible on-site rather than being exported to the grid at lower rates. The BESS stores excess solar energy during the day for use during the night or periods of low generation.	Maximizing self-consumption reduces dependency on grid electricity, leading to substantial savings on energy bills. These savings contribute to the revenue stack, resulting in a faster recovery of the BESS investment.
Frequency Regulation (FR) and Ancillary Services	Providing grid services such as frequency regulation, voltage support, and spinning reserve can generate additional income. Utilities and grid operators often pay for these ancillary services to maintain grid stability and reliability.	Participating in these markets provides a steady revenue stream, adding to the revenue stack and ensuring a quicker payback period.

Capacity Market (CM)	Capacity markets allow BESS owners to receive payments for being available to supply energy during high-demand periods, ensuring sufficient capacity for grid stability.	By participating in these markets, the BESS earns additional income simply by being available, which adds to the revenue stack and contributes to faster investment recovery.

Table 1. Description and benefits of the different operating modes (i.e. control strategies) that will be implemented in the Smart EMS.

By leveraging revenue stacking, a BESS can strategically utilize multiple revenue streams and cost-saving opportunities. Each operating mode enhances the economic performance of the BESS by either increasing revenue or reducing costs. This diversified approach ensures that the system consistently generates financial returns from various sources. The combination of cost savings through reduced peak demand and energy bills, revenue from market arbitrage, ancillary services, and other value-added applications means that the system could pay for itself in a relatively short timeframe. It is also worth noting that the right combination of several control strategies might **Avoid Grid Reconstruction (AGR)** which is also translated into to cost savings**.** Thus, a well-implemented BESS with versatile operating modes and a revenue stacking strategy justifies the initial investment through its quick amortization.

The starting point of the system for PVOP project, resulting from the first cycle of WATT incremental development strategy, already integrates several of the operation modes described in the table above, such as: Time of Use, Peak Shaving, a quite premature Network Arbitrage, Self-consumption Maximization and the first specification of the Smart Predictive mode.

Not only are grid ancillary services and grid demands strategies still to be implemented, but there is also room for improvement of existing strategies. For the system to coordinate with the grid and its requirements, it needs to evolve to a higher level, in which it acquires the ability to control other energy terms, such as reactive power. Regarding the improvement of the existing operating modes, control engineering methods are being studied to stabilize the system response and guarantee the best behaviour, which could involve, for example, methods in states space or in the frequency domain. The aim is also to improve the inference capabilities of the system to anticipate future behaviours. While electricity prices or some solar incidence parameters are currently consulted through the cloud and used for small-term prediction, many others can be integrated, such as the behavioural patterns of the installation, other meteorological factors and even neural networks that learn from the performance of the controller to give it feedback or that model the transfer function of the entire set. Among all the improvements, those that are viable within the scope of the project and that align with its objectives will be chosen.

Regarding all these strategies, WATT EMS will receive inputs from sensors, electricity price databases, meteorological databases and Electricity Market Analysts as ASIC XXI (this last one described in chapter B). In relation to this last point, WATT and ASIC will agree on an **Application Program Interface**, **API**, to interchange information. WATT will provide actual technical restrictions of the BESS system (such as SOC, Maximum Power…) and ASIC XXI will provide instructions for charging and discharging depending on market opportunities for additional revenue.

3.1.3. Control strategies, algorithms and KPIs

The KPIs defined in this deliverable are divided into two categories: first, the KPIs necessary to evaluate if a certain control strategy was correctly implemented; second, the KPIs that quantify the impact of the battery integration for a certain application. The KPIs for the impact are strongly dependent on the system where the battery is integrated, and are affected by external factors like the size of the system, the consumption profiles, the electricity prices… Hence, such KPIs will be defined but not quantified, as there is not enough information available.

3.1.3.1. KPIs for the implementation of the control strategies

Figure 4 shows the schematic of a system with the following components:

- PV generator: it generates DC power (P_{PV})
- Li-ion battery: it exchanges DC power when it is charging ($P_{ch,B}$) or discharging ($P_{dis,B}$)
- Consumer: it consumes AC power (P_{cons})
- Electric grid: it permits to import AC power ($P_{imp,G}$) or to export it ($P_{exp,G}$)

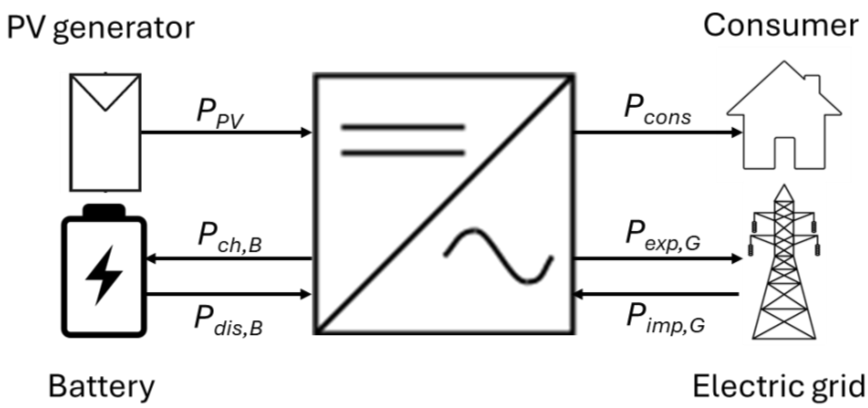

Figure 1. Schematic of a system with a battery integrated, showing the different power exchanges.

The battery permits to implement different control strategies with different objectives. In this section, it is explained how to evaluate the correct implementation of such strategies, attending to two different levels:

1. **Algorithm implementation:** first, it is necessary to evaluate if the battery responds to what the controller orders it to do, depending on the different control logics. The Root Mean Squared Error (RMSE) will be used as a metric to evaluate the accuracy of the performance of the battery's power output. In this case, the RMSE measures the discrepancy between the predicted power output of the battery and the actual power output, based on a given set of power set points under specific State of Charge (SOC) conditions.

   The equation for RMSE is expressed as:

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_{\text{predicted},i} - P_{\text{actual},i})^2}$$

Where:

- $\mathbf{P}_{\mathbf{predicted,i}}$ represents the predicted power output of the battery at time i, calculated based on the power set points and SOC conditions.
- $\mathbf{P}_{\mathbf{actual,i}}$ represents the actual measured power output of the battery at time i. It can be $P_{ch,B}$ or $P_{dis,B}$ depending if battery is charging or discharging
- n is the total number of observations.

In this context, the set points for power define the desired power output levels, and the SOC represents the current charge level of the battery, which can influence its ability to deliver or absorb power. The RMSE quantifies the precision of the battery model by summarizing how closely the predicted power output matches the actual output across various conditions. A lower RMSE value indicates higher accuracy, meaning the model more accurately reflects the battery's real-world behaviour.

Note that this KPI is independent of external factors, like solar irradiance or electricity consumption, and do not consider whether the size of the battery is optimized or not.

Note that this RMSE threshold is defined under the nominal standard operating conditions of the system, excluding from this value the boundary conditions under which the system exhibits responses not studied at this point of the project, that could affect the RMSE calculation. The previous includes factors, among others, such as the battery cell and ambient temperatures and the SOC status of the system, since this value approaching its upper end implies that some battery packs will be full of charge while others will not, causing the maximum instantaneous charging power to decrease. Similarly, low SOC percentages produce the same not yet studied effect on power setpoint performance. The nominal conditions will then be defined together with their corresponding thresholds for the proposed KPIs.

2. **Algorithm impact (functionality of the strategy):** once that it is guaranteed that the implementation of the algorithms is validated as correct, i.e., the battery operates at the set point that corresponds to each strategy in any operating situation, it is necessary to evaluate if the control strategy implemented has the expected impact on the system. For this, different KPIs will be required for each control strategy, attending to their ultimate objective. These KPIs are dependent on external factors, like solar irradiance or the electricity consumption, and on the sizing of the battery. However, at this point of the project it is almost impossible to estimate which values could be expected for these KPIs, so in this deliverable they will be only qualitatively defined, and their quantification will be the objective of future work.

The following section lists and describes all the control strategies that will be implemented, explaining how the code calculates the set point of the battery (**set point variables are highlighted in green**, indicating that it is necessary to guarantee that the RMSE between the calculated and the measured values is lower than OJO%) and defining the KPIs to evaluate the impact on the system. Note that there will be situations when the battery is not capable of fulfilling the strategy objective (when it is completely charged or discharged). These situations will be indicated with a **warning message highlighted in red**.

1) **Time of Use Arbitrage (TOU):** typically, TOU arbitrage involves charging the battery during off-peak hours when electricity prices are low and discharging during peak hours when prices are high. This process allows the BESS

to capitalize on price differentials by buying low and selling high. However, TOU can also refer to a strategy that defines periods when it is convenient to import/export electricity from the grid, attending to criteria that are not necessarily economic. In this case, there are two factors to consider: when are the import/export periods, and what is the power that should be exchanged with the electric grid. The set point of the battery will be a consequence of both factors and of the State of Charge (SOC).

Algorithm implementation

0% < SOC < 100%:

- Import period (charging the battery): $\mathbf{P_{ch,B}} = P_{imp,G} + P_{PV} – P_{cons}$
- Export period (discharging the battery): $\mathbf{P_{dis,B}} = P_{exp,G} - P_{PV} + P_{cons}$

SOC = 100%:

- Import period (charging the battery): **WARNING**
- Export period (discharging the battery): $\mathbf{P_{dis,B}} = P_{exp,G} - P_{PV} + P_{cons}$

SOC = 0%:

- Import period (charging the battery): $\mathbf{P_{ch,B}} = P_{imp,G} + P_{PV} – P_{cons}$
- Export period (discharging the battery): **WARNING**

The KPIs for the correct implementation of the algorithm is:

- $KPI1_{TOU}$: RMSE ($P_{dis/ch,B}$ - $P_{dis/ch,B\ measured}$) < 2%. It evaluates the goodness of the algorithm to establish the setpoint of the power of the battery. NOTE: the operational conditions for which the upper $KPI1_{TOU}$ value is proposed are 20%<=SOC<=80% @ 0º-40º.

- $KPI2_{TOU}$: $t_{transition}$ < 2s. It evaluates the time of the transition between the import and export periods.

Algorithm impact

- $KPI3_{TOU}$: it evaluates if the power imported or exported from the grid is the one stablished for every period. It is the RMSE between the calculated import/export power values and the measured values of $P_{imp,G}$ and $P_{exp,G}$.

- $KPI4_{TOU}$: it evaluates if energy is imported/exported from the grid when it should. For a certain period, it is calculated as follows:

$$KPI4TOU = \frac{Energy\ exchanged\ with\ the\ grid\ during\ TOU\ hours}{Energy\ exchanged\ with\ the\ grid}$$

- $KPI5_{TOU}$: for the specific case when the TOU hours are defined attending to the electricity tariffs, the power exchanged with the grid is limited to the contract power with the electric company ($P_{max,G}$). The electricity company does not measure the power in real time but measures the energy consumption every 15 minutes. So, it is important to assure the following:

$$\int_{t1}^{t2} P_{imp/exp,G} \leq P_{max,G} \times (t_2 - t_1)$$

where $(t_2 - t_1)$ corresponds to periods of 15 minutes and $P_{imp/exp,G}$ can be the imported or exported energy from the grid in that period of time.

2) **Peak shaving (PS):** Peak shaving reduces the demand charges on electricity bills by lowering the peak demand during high-consumption periods. By discharging the battery during peak times, businesses can avoid the highest tariff rates associated with their peak usage. For this control strategy, the main parameter is the maximum power that can be exchanged from the grid ($P_{max,G}$), whether it is imported or exported.

Algorithm implementation

0% < SOC < 100%:

- If $P_{PV} > (P_{max,G} + P_{cons})$ then charge the battery: $\mathbf{P_{ch,B}} = P_{PV} – P_{max.G} - P_{cons}$
- If $P_{cons} > (P_{max,G} + P_{PV})$ then discharge the battery: $\mathbf{P_{dis,B}} = P_{cons} – P_{max.G} – P_{PV}$

SOC = 100%:

- If $P_{PV} > (P_{max,G} + P_{cons})$ then charge the battery: **WARNING**
- If $P_{cons} > (P_{max,G} + P_{PV})$ then discharge the battery: $\mathbf{P_{dis,B}} = P_{cons} – P_{max.G} – P_{PV}$

SOC = 0%:

- If $P_{PV} > (P_{max,G} + P_{cons})$ then charge the battery: $\mathbf{P_{ch,B}} = P_{PV} – P_{max.G} - P_{cons}$
- If $P_{cons} > (P_{max,G} + P_{PV})$ then discharge the battery: **WARNING**

The KPIs for the correct implementation of the algorithm is:

- $KPI1_{PS}$: RMSE ($P_{dis/ch,B}$ - $P_{dis/ch,B\ measured}$) < 2%. It evaluates the goodness of the algorithm to establish the setpoint of the power of the battery. NOTE: the operational conditions for which the upper $KPI1_{PS}$ value is proposed are 20%<=SOC<=80% @ 0º-40º.

- $KPI2_{PS}$: $t_{transition}$ < 2s. Evaluates the transition time from one power setpoint to another when sudden setpoint changes occur.

Algorithm impact

- $KPI3_{PS}$: RMSE ($P_{imp/exp,G}$ - $P_{max,G}$). It evaluates if the power imported or exported from the grid does not exceed the maximum permitted value. It is the RMSE between $P_{max,G}$ and the measured values of $P_{imp,G}$ and $P_{exp,G}$, considering only the periods when the battery should actually peak shave.

- $KPI4_{PS}$: it evaluates if the electricity company would penalize the user of the battery for exceeding $P_{max,G}$. Considering that the electricity company does not measure the power in real time, but only measures the energy consumption every 15 minutes, it is important to assure the following:

$$\int_{t1}^{t2} P_{imp/exp,G} \leq P_{max,G} \times (t_2 - t_1)$$

where $(t_2 - t_1)$ corresponds to periods of 15 minutes and $P_{imp/exp,G}$ can be the imported or exported energy from the grid in that period of time.

3) **Maximization of self-consumption (MSC):** This mode ensures that energy generated by a solar PV system is used as much as possible on-site rather than being exported to the grid at lower rates. The BESS stores excess solar energy during the day for use during the night or periods of low generation. This objective can also be understood as minimizing the energy exported to the grid.

Algorithm implementation

0% < SOC < 100%:

- If $P_{PV} > P_{cons}$ then charge the battery: $\mathbf{P_{ch,B}} = P_{PV} - P_{cons}$
- If $P_{cons} > P_{PV}$ then discharge the battery: $\mathbf{P_{dis,B}} = P_{cons} - P_{PV}$

SOC = 100%:

- If $P_{PV} > P_{cons}$ then **export to the grid**: $\mathbf{P_{exp,G}} = P_{PV} - P_{cons}$
- If $P_{cons} > P_{PV}$ then discharge the battery: $\mathbf{P_{dis,B}} = P_{cons} - P_{PV}$

SOC = 0%:

- If $P_{PV} > P_{cons}$ then charge the battery: $\mathbf{P_{ch,B}} = P_{PV} - P_{cons}$
- If $P_{cons} > P_{PV}$ then import from the grid: $\mathbf{P_{imp,G}} = P_{cons} - P_{PV}$

The KPIs for the correct implementation of the algorithm is:

- $KPI1_{MSC}$: RMSE ($P_{dis/ch,B}$ - $P_{dis/ch,B\ measured}$) < 2%. It evaluates the goodness of the algorithm to establish the setpoint of the power of the battery. NOTE: the operational conditions for which the upper $KPI1_{MSC}$ value is proposed are 20%<=SOC<=80% @ 0º-40º.

- $KPI2_{MSC}$: $t_{transition}$ < 2s. Evaluates the transition time from one power setpoint to another when sudden setpoint changes occur.

Algorithm impact

- $KPI3_{MSC}$: Self-Consumption Rate (SCR): it is the portion of the total PV energy that is consumed in the system, whether directly or previously storing it in the battery.

$$SCR = \frac{E_{PV}^{C} + E_{B}^{C}}{E_{PV}}$$

  Where E_{PV}^{C} is the PV energy that is directly consumed, E_{B}^{C} is the energy consumed from the battery and E_{PV} is the total energy produced.

- $KPI4_{MSC}$: Surplus Energy Rate (SER): it is the portion of the total PV energy that is exported to the grid.

$$SER = 1 - \frac{E_{PV}^{C} + E_{PV}^{S}}{E_{PV}}$$

  Where E_{PV}^{S} is the PV energy that is stored in the battery.

4) **Frequency Regulation (FR):** Providing grid services such as frequency regulation, voltage support, and spinning reserve can generate additional income. Utilities and grid operators often pay for these ancillary services to maintain grid stability and reliability. From the different types of grid regulation, batteries can contribute to frequency regulation, as they are capable of delivering or absorbing active power (reactive power, on the other hand, is how the grid voltage is regulated).

* The standard frequency in Europe's electricity grid is 50 Hz. In North America and parts of Japan, on the other hand, a standard frequency of 60 Hz is used. In any case, there is always a tolerance for this value. For general purposes, we will call $freq_{SP}$ to the stablished frequency in each grid and consider a ±Tolerance.

*For this control strategy, the frequency regulation will be translated into the power that might be demanded from the grid according to the setpoint established by the grid operator, whether it is imported or exported for grid stabilization (so, here $P_{imp,G}$ and $P_{exp,G}$ means the setpoints established by the grid operator). There is also a maximum time of response, established by the electric grid operator ($t_{max,FR}$), that is crucial for this strategy.

Algorithm implementation

0% < SOC < 100%:

- If frequency > ($freq_{SP}$ + Tolerance) then import from the grid (charging the battery): $\mathbf{P_{ch,B}} = P_{imp,G} + P_{PV} - P_{cons}$
- If frequency < ($freq_{SP}$ - Tolerance) then export to the grid (discharge the battery): $\mathbf{P_{dis,B}} = P_{exp,G} - P_{PV} + P_{cons}$

SOC = 100%:

- If frequency > ($freq_{SP}$ + Tolerance) then import from the grid (charging the battery): **WARNING**
- If frequency < ($freq_{SP}$ - Tolerance) then export to the grid (discharge the battery): $\mathbf{P_{dis,B}} = P_{exp,G} - P_{PV} + P_{cons}$

SOC = 0%:

- If frequency > ($freq_{SP}$ + Tolerance) then import from the grid (charging the battery): $\mathbf{P_{ch,B}} = P_{imp,G} + P_{PV} - P_{cons}$
- If frequency < ($freq_{SP}$ - Tolerance) then export to the grid (discharge the battery):
  If $P_{PV} > P_{cons} + P_{exp,G}$ then $P_{exp,G}$ imported to the grid is dispatched from P_{PV}
  If $P_{PV} < P_{cons} + P_{exp,G}$ then discharge battery: **WARNING**

The KPIs for the correct implementation of the algorithm is:

- $KPI1_{FR}$: RMSE ($P_{dis/ch,B}$ - $P_{dis/ch,B\ measured}$) < 1%. It evaluates the goodness of the algorithm to establish the setpoint of the power of the battery. NOTE: the operational conditions for which the upper $KPI1_{FR}$ value is proposed are 20%<=SOC<=80% @ 0º-40º.

- $KPI2_{FR}$: $t_{transition}$ < 2s. Evaluates the transition time from one power setpoint to another when sudden setpoint changes occur.

Algorithm impact

- $KPI3_{FR}$: RMSE ($P_{imp/exp,G}$ - $P_{imp/exp,G\ measured}$). It evaluates if the power imported or exported from the grid is the one stablished for every demand period. It is the RMSE between the calculated import/export power values and the measured values of $P_{imp,G}$ and $P_{exp,G}$.

- KPI4$_{FR}$: it is the percentage of $t_{max,FR}$ that the battery took to react. It is defined as follows:

$$KPI2_{FR} = \frac{t_{max,FR} - t_{react}}{t_{max,FR}} x100$$

5) **Capacity markets (CM):** allow BESS owners to receive payments for being available to supply energy during high-demand periods, or absorbing energy during high-production periods, ensuring sufficient capacity for grid stability. For this strategy we will consider that capacity markets may demand support for both the supply of power to the grid (export period) or the reduction of power from the grid (import period). So, here $P_{imp,G}$ and $P_{exp,G}$ means the setpoints established by the capacity markets. There is also a maximum time of response, established by the electric grid operator ($t_{max,CM}$), that is crucial for this strategy.

Algorithm implementation

0% < SOC < 100%:

- Import period (charging the battery): $\mathbf{P_{ch,B}}$ = $P_{imp,G} + P_{PV} – P_{cons}$
- Export period (discharging the battery): $\mathbf{P_{dis,B}}$ = $P_{exp,G} - P_{PV} + P_{cons}$

SOC = 100%:

- Import period (charging the battery): **WARNING**
- Export period (discharging the battery): $\mathbf{P_{dis,B}}$ = $P_{exp,G} - P_{PV} + P_{cons}$

SOC = 0%:

- Import period (charging the battery): $\mathbf{P_{ch,B}}$ = $P_{imp,G} + P_{PV} – P_{cons}$
- Export period (discharging the battery):
  If $P_{PV} > P_{cons} + P_{exp,G}$ then $P_{exp,G}$ exported from grid is dispatched from P_{PV}
  If $P_{PV} < P_{cons} + P_{exp,G}$ then discharge battery: **WARNING**

The KPIs for the correct implementation of the algorithm is:

- KPI1$_{CM}$: RMSE ($P_{dis/ch,B}$ - $P_{dis/ch,B\ measured}$) < 2%. It evaluates the goodness of the algorithm to establish the setpoint of the power of the battery. NOTE: the operational conditions for which the upper KPI1$_{CM}$ value is proposed are 20%<=SOC<=80% @ 0º-40º.

- KPI2$_{CM}$: $t_{transition}$ < 2s. Evaluates the transition time from one power setpoint to another when sudden setpoint changes occur.

Algorithm impact

- KPI3$_{CM}$: RMSE ($P_{imp/exp,G}$ - $P_{imp/exp,G\ measured}$). It evaluates if the power imported or exported from the grid is the one stablished for every period. It is the RMSE between the calculated import/export power values and the measured values of $P_{imp,G}$ and $P_{exp,G}$.

- KPI4$_{CM}$: it is the percentage of $t_{max,CM}$ that the battery took to react. It is defined as follows:

$$KPI4_{CM} = \frac{t_{max,CM} - t_{react}}{t_{max,CM}} x100$$

6) **Demand management (DM):** aim to manage and balance the supply and demand of electricity in real-time, responding to fluctuations in consumption and energy generation. Both energy providers (generators) and consumers who can reduce their demand in response to signals from the system operator participate in these markets.

   * The algorithm implementation of this strategy is very similar to the one developed for peak shaving except that in this case the max power from the grid is not a fixed value and can vary according to real time demand. So, the same strategy and PIs will be used.

3.1.3.2. KPIs for the impact of battery integration

The **impact of implementing the Smart EMS in the control system** of a PV installation needs to be somehow quantified, to determine whether it is beneficial or not. This section details the KPIs proposed to evaluate different aspects of the innovations implemented. These KPIs are structured in three levels:

1. **General KPIs**: related to the general objectives of T3.2, which are maximizing the performance and the energy trading of the PV installation. They will be obtained by comparing a certain PV installation with and without batteries, in terms of performance and economic profitability. This way, the KPIs will quantify the benefits of including the Smart EMS developed at PVOP. We will simulate both plants using digital twins: first, we will replicate the production of a given installation without battery; second, we will simulate its production with the battery and the advanced control system. We expect approximate increments of the annual energy yield of 5% (based on avoidance of technical curtailments at the point of injection by means of deviating the excess of instantaneous solar production to the battery) and a minimum reduction of the LCOE of 10% (based on correct energy arbitrage strategies) both calculated for a 30-year span.

Calculation of the Levelized Cost of Storage (**LCOS**) of a BESS installation is a measure of the average cost per unit of electricity that is stored and then discharged by an energy storage system over its lifetime. It is used to evaluate the economic performance and cost-effectiveness of different energy storage technologies, such as batteries. To give real LCOS numbers we need to study the performance of the system for approximately one year. The WATT EMS system has not been deployed for that long, so it is not yet possible to give very accurate data on this. But it is expected that over the course of the PVOP project this figure will not only be known but can be reduced based on different implementations and improvements of the battery energy strategies.

2. **Specific KPIs**: specific to the application. In this case, the outcome of the system depends on too many external factors, so these KPIs will be conceptually defined, but not quantified for now.

- PV plants: the performance of grid-connected PV plants is typically evaluated through the **Performance Ratio (PR)**, which is the ratio between the AC energy delivered to the grid and the DC energy that could have been ideally produced, for a certain period of time. Including a battery could delay in time the AC energy injection but should reduce it because the battery efficiency losses. The **battery integration** generally results in a lower PR compared to a system without a battery, but it adds value by allowing stored energy to be used at optimal times for the grid, improving overall energy management.

- Large self-consumption: these installations are typically evaluated thorough the **Self-Consumption Rate (SCR)** -the fraction of PV energy that is consumed in situ from the total PV energy produced- and the **Self-Sufficiency Rate (SSR)** -the fraction of energy that comes from the PV generator from the total energy consumption-. Incorporating **a battery in a self-consumption installation can increase both rates, specially the SSR**; the SCR is highly dependent on the consumption profiles, and if they are too decompensated from the PV generation, the battery needed to increase the SCR would be too big to be economically feasible.

- New niches:

  - **Energy communities:** can be characterized by the same KPIs as self-consumption installations: **the SCR and the SSR**. However, it should be noted that the SCR is strongly affected by the proportion between the members of the community that install PV generators and the members who are only consumers. If few generators provide electricity for many consumers, the energetic surplus must increase to the detriment of the SCR.

  - **Mining:** batteries in mining installations are crucial for **reducing the consumption of diesel fuel**, that is both pollutant and expensive (and the prices are expected to keep increasing). The idea is to use diesel generators only as back-up for the periods when the PV power is reduced or the consumption increases. For guaranteeing the stability of the system, **it is critical that batteries can power the whole mine, self-sufficiently, during the 10 minutes that take diesel generators to be turned on**. For this, meteorological forecasting will be fundamental.

3. **Fundamental KPIs:** to reach the objective values for the general KPIs, it is necessary to guarantee the technical quality of the different solutions implemented. It is difficult to imagine all the relevant technical KPIs that will be involved, but at least the following must be considered:

   - Accuracy in the estimation of the SOC: To increase the operational and financial reliability of all BESS systems it is necessary to have accurate state of charge estimations which are essential for reliable operation by increasing the accuracy of the estimated energy available for discharge. A recent report alerts that conventional SOC measurements can result in average errors of 7% when the EMS estimates the energy available in the battery. An independent assessment of the SOC will be carried out. We will monitor the current flows in and out of the battery with very accurate sensors (quantifying any possible offset) and will account for the internal architecture connecting cells (advanced EMS use more complex strategies, with a significant impact on the energy availability). With this, we intend to reduce **average errors to 3% in the estimation of the energy available**.

   - Accuracy in the estimation of the SOH: The battery degrades not only because of the aging that it suffers due to the fact of being stopped only and exclusively by the passage of time, but also because of the number of cycles it has throughout its life (cycling aging). We will develop and implement aging models for the different control strategies in the advanced EMS. This way, the degradation induced by a certain cycling of the battery will be considered when selecting one control strategy or another. Also, we will perform regular tests for **comparing the estimated SOH, according to the implemented models, and the real one: the difference should be less than 7%** at the end of the project, after the aging models have been correctly tuned.

3.1.3.3. Implementation of the Smart EMS

A. Implementation at the IES-UPM outdoor testing facilities

The solutions will be developed, and a first validation (during the first 18 months of PVOP project) will be carried out **at prototype-alpha level in controlled environments (at IES-UPM battery)**. It is planned to be installed a 15 kWp PV System prototype with an integrated 100 kW battery and 97 kWh capacity at UPM facilities by WATT at the beginning of the project. At this stage (during month 6 of the project), an alpha version of API interface between Wattkfrat and ASIC XXI will be provided. This API version will continue to develop over the next months of the project. The following planification of the battery installation is briefly explained:

- Battery Selection: DONE (Manufacturer & Model: Huawei LUNA2000 97KWh)
- Emplacement validation based on technical and safety restrictions evaluation: DONE (internal yard at the ETSIT campus has been selected in agreement with the University)
- Procuring and Delivering (lead time > 22 weeks -> Critical path): ETA October 2024.
- Contract for executing Civil works and installation: IN PROGRESS
- Battery Commissioning and Field Acceptance Tests: Planned During November 2024 after installation

Figure 2. Battery selected for the PVOP project

B. Implementation at a commercial PV plant

On a second period of the project, the technical solutions will be implemented and validated **in real PV plants.** WATT EMS development process will follow an engineering and empirical approach: incremental integration of functionalities to be promptly tested on real batteries. This approach will yield a time to market functional product.

Figure 6 shows one of the pilot sites for testing beta EMS version, already in operation since March 2024.

Figure 3. One of the pilot sites for testing beta EMS version in operation since March 2024

Site 1: Installation of 12.6MWn PV + 10MWh/5MW BESS

- FV: 12.6MWn (64xHuawei SUN2000-215KTL-H0 inverters)
- BESS: 10MWh/5MW
- COD: March 2024
- Control: Power Plant Controller + EMS integrated in the factory SCADA

3.1.4. Conclusions

This chapter is intended to evaluate the **control of PV plants with storage systems**, what control strategies are most interesting and how they could be combined and optimized by a smart EMS. The following innovations are proposed:

- AI-based electricity market predictions (detailed in chapter B), that will be an input for the EMS.
- Weather conditions predictor will be used as input for the EMS.
- The EMS will decide every hour what the most suitable battery control strategy is and implement it, instead of only operating according to one strategy.
- SOC estimations will be performed in parallel to the EMS, to reduce the error.
- Aging models will be implemented for a more accurate estimation of the SOH.

This report paves the way for the next PVOP experimental steps, that must lead to developing an advanced control system for PV systems with batteries. For that, the validation experiments will be implemented in two phases: at the

IES-UPM outdoor testing facilities and at a few commercial PV installations. Corresponding KPIs, based on the **maximization of the performance and the energy trading** of the PV installation, are proposed.